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Application Of Finite Element Analysis (Fea) To Fiber-Reinforced Composite Of Recycled High Density Polyethelene

Susan X. Shao
Eastern Illinois University

APPLICATION OF FINITE ELEMENT ANALYSIS (FEA) TO FIBER-REINFORCED COMPOSITE OF RECYCLED HIGH DENSITY POLYETHYLENE

SHAO

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Application of Finite Element Analysis (FEA) to Fiber-Reinforced

Composite of Recycled High Density Polyethylene

(TITLE)

BY

Susan X. Shao

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Larry D. Helsel
ADVISER

12/1/93
DATE

Larry D. Helsel
DEPARTMENT HEAD

THESIS COMMITTEE MEMBERS

Larry D. Helsel
12/1/93

Larry D. Helsel, Ed.D.
Professor, Chair
School of Technology

Date

Strandberg
1 Dec 93

Clifford E. Strandberg, Ed.D.
Professor
Graduate Student Adviser
School of Technology

Date

Tom Waskom
12/1/93

Tommy L. Waskom, Ph.D.
Professor
School of Technology

Date

12-1-93

Mahyar Izadi, Ph.D., CMfgE
Associate Professor
School of Technology

Date

ABSTRACT

Title of thesis: **Application of Finite Element Analysis (FEA) to Fiber-Reinforced Composite of Recycled High Density Polyethylene.**

It is known that the property of fiber-reinforced composite is dependent upon the matrix type, fiber size, orientation and distribution. Optimization of all these parameters is critical to achieve the best property of the composite. Finite element analysis was used to model fiber-reinforced composites of recycled high density polyethylene.

The objectives of this research were: (1) to study the effect of fiber aspect ratio (fiber size) and fiber orientation on the stress distribution in the composite material; and (2) to investigate the reinforcing effect of glass fiber on the composite using finite element analysis.

The effect of fiber reinforcement was studied in terms of the stress distribution between glass-fiber (E fiberglass) and high density polyethylene (HDPE) matrix. A finite element analysis software package called Algor was used in this research. The following conclusions were made according to the finite element analysis results on glass-fiber-reinforced thermoplastic composite of recycled high

density polyethylene:

1. The geometrical model and Algor processor were proven to be adequate for the analysis of the thermoplastic composite.

2. A stress partition ratio (SPR) had been introduced successfully to evaluate the load bearing capability of fibers in the composite. The load bearing capability of the fiber is directly proportional to the stress partition ratio (SPR).

3. As the fiber aspect ratio increased up to 20, the stress in fiber increased, the stress in matrix decreased and therefore stress partition ratio increased. The aspect ratio of 20 for the glass fiber may give the optimum strength of the composite.

4. As the fiber orientation angle increased, the stress in fiber decreased and the stress in matrix increased. Those changes resulted in the decrease of stress partition ratio as the fiber orientation angle increased. Fibers aligned in the tension load direction provided the best load carrying capability.

DEDICATION

I dedicate this work to my husband Ping Liu, who has been beside me and has helped to motivate and support me throughout my graduate career. His love and his technical support are crucial to the success of this research.

I also dedicate this work to our beautiful daughter Annie Liu for her dear cooperation. She has shown me how important being a mother is and she is my inspiration for knowledge.

I sincerely dedicate this work to my parents for their dreams, their support, their sacrifice, their encouragement, their love and their affection.

ACKNOWLEDGMENTS

It has been an honor to work under the supervision of Dr. Larry D. Helsel and Dr. Clifford E. Strandberg and I extend my deepest gratitude to them for their continuous guidance, constant encouragement and patient assistance.

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CHAPTER I

Introduction

The solid waste disposal crisis has emerged as a primary concern of environmental protection and natural resource conservation due to the decreasing number and space of landfills. As landfill capacity declines, the rate at which American produces garbage is accelerating by leaps and bounds. It was estimated that the solid waste generated in the United States would grow at an average of 1.8 percent per year into the next century (Goldstein, 1989). By the beginning of the 21st century, Americans will produce more than 180 million tons of solid waste every year, or 3.7 pounds per day per person (Goldstein, 1989). It is imperative to find effective means of reducing the solid waste in order to preserve the environment. It was reported that plastics occupied up to 21% of landfill volume by 1990 and the amount of plastic waste was predicted to increase by 50% by the year 2000 (United States Environmental Protection Agency, 1990). Plastic recycling, therefore, will play a significant role in reducing solid waste flow to landfills and in conserving natural resources.

A typical problem associated with plastic recycling is that recycled plastics have inferior properties compared with their virgin counterparts; also, a lack of design analysis tools limits applications of recycled plastics. To promote plastic recycling, research sponsored by the Illinois Department of Energy and Natural Resources is currently being conducted on "Thermoplastic Composites of Recycled High Density Polyethylene (HDPE) Reinforced by Short Glass Fibers" (Liu & Waskom, 1993). The new composite is expected to have properties superior to plastics without reinforcement, thereby allowing the recycled material to compete with virgin resins in cost and material properties. However, the extensive application of the recycled material requires a comprehensive understanding of the role of fibers in the composite to optimize the behavior of the composite.

It is known that the property of a fiber-reinforced composite is dependent upon matrix type, fiber size, orientation and distribution. Optimization of all these parameters is critical to achieve the best property of the composite. As an effective tool of evaluating stress, deformation and potential failure of materials, finite element analysis can be used for design optimization. It can reduce the lead time for product development, save product or prototype test cost and predict the safety and quality of the products. Finite element analysis can be used to model composite materials so that more understanding of the composite behavior, especially the reinforcing effect of fibers, can be achieved. However, the application of the computational modeling and analysis to recycled plastic composite is a completely new field due to the complexity involved in the composite structure.

The objectives of this research were: (1) to study the effect of fiber aspect ratio (fiber size) and fiber orientation on the stress distribution in the composite material; and (2) to investigate the reinforcing effect of glass fiber on the composite by using finite element analysis.

Finite element analysis was performed on a microcomputer to study the stress distribution of the polymeric composite and the role of glass fibers in reinforcing recycled plastic. The analysis provided a better understanding on the relationship of glass fiber reinforcement to the recycled plastic. The effects of fiber reinforcement were studied in terms of the stress distribution between glass fiber and high density polyethylene (HDPE) matrix.

CHAPTER II

Literature Review

Finite element analysis (FEA) is a numerical tool that can be applied effectively to the analysis of many physical and mathematical models for engineers and scientists. These physical and mathematical models usually arise in the process of modeling problems in application areas such as solid and fluid mechanics, heat transfer, vibrations, electrical potentials and magnetic fields. Finite element analysis first appeared in the 1950s as a technique of solving problems in solid mechanics. The mathematical basis of the technique renders it applicable to problems throughout applied mathematics, continuum mechanics, engineering and physics (Tong & Rossettos, 1977). Particularly, FEA is an extremely powerful tool in optimizing part design (Bickford, 1990).

Finite element analysis of a problem is so systematic that it can be divided into a set of logical steps which can be implemented on a digital computer and can be used to solve a wide range of problems by merely changing the data input defining the domain including physical properties and initial or boundary conditions. It is this feature that gives finite element analysis such remarkable success in the modeling and simulation of practical engineering problems (Ochoa & Reddy, 1992).

Finite element analysis entails the solution of a very large number of equations for the nodal values of the function being sought. The number of equations is equal to the number of unknown nodal values. Thus the analysis requires so much computation that it is practical only if the calculations are performed by a computer.

Composite materials are fabricated to have better engineering properties than conventional materials. Some of the properties that can be improved by forming a composite material are: stiffness, strength, corrosion resistance, thermal properties, fatigue life and wear resistance. Thus, composite materials are most suitable in applications that require high strength-to-weight and stiffness-to-weight ratios. They are increasingly used in aircraft structures, automobiles, sports equipment, medical prosthetic devices and electronic circuit boards.

Most composites are made from two constituents: a reinforcement material and a matrix. Short fibers are currently being introduced into sheet-molding compounds (SMC), metal matrix composites (MMC), brittle matrix composites (BMC) and a variety of other materials to enhance the mechanical properties exhibited by these composites. With the increased use of fiber-reinforced composites in structural components, studies involving the behavior of components made of composites are receiving considerable attention. Functional requirements and economic considerations of the design are forcing engineers to seek reliable and economical methods of determining static and dynamic characteristics of the structural components (Ochoa & Reddy, 1991). Understanding the reinforcing effect of fiber on composites is crucial to optimize the structures.

The scientific community endeavors to represent theoretically the complex interaction between the short fibers and the surrounding matrix, both globally and locally, in an attempt to infer material behavior. Many investigations have been conducted on the reinforcing effect of fiber for composites. In the study conducted by Hwang and Gibson (1987), finite element analysis was used to predict the fiber interaction and fiber interface effects on composite damping. The results showed that fiber interaction did affect the damping of discontinuous fiber composites and that damping can be improved by increasing the fiber end gap or by decreasing the fiber aspect ratio. It was also shown that the finite element implementation of the strain energy approach was a powerful tool for predicting the damping in composites (Hwang & Gibson, 1987). In the research conducted by Hom (1992), three-dimensional finite element calculations were performed to predict quantitatively the tensile behavior of a metal matrix composite reinforced with aligned short fibers. Hom's analysis examined the strengthening effect of the whiskers under macroscopic uniaxial tension loads in the fiber direction and uniaxial tension in a direction perpendicular to the fiber. The finite element analysis results showed that the material's load carrying capacity in a direction transverse to the fiber was significantly lower than that along the fiber direction.

High speed computers combined with finite element analysis provides a powerful tool in simulating composite structures and optimizing various parameters. In the study conducted by Sun and Chen (1992), finite element analysis was used to understand the elastic-plastic response of laminated thermoplastic composite plates and shells. In another investigation by Kwon and Byun (1991), a model and its finite element formulation have been developed to analyze fiber-reinforced composite structures with some local damage such as matrix cracks. In their study, the stresses acting in fibers and the stresses acting in matrix were computed directly using the theoretical models.

The mechanisms of deformation and failure can be interpreted in terms of the state of stress and strain. An analytical model applied to composites were presented by Carman and Reifsnider (1992) to predict the point-wise stresses in the fiber and the matrix including the stress state at fiber ends. Their modeled composite involved varying fiber orientations, different fiber lengths and different fiber types. The stiffness tensor of the composite was calculated by globally averaging the approximate stresses in the representative fiber and matrix of the composite.

FEA software has now reached a level of development which makes the analysis a practical tool for design engineers. Though finite element analysis has been used successfully to perform stress analysis for product design and analysis of traditional engineering materials and composites, its application was limited to mainframes. Recent advances in microcomputers and software development make it possible to perform this complex computational analysis on microcomputers which are much more accessible to industry. No systematic study was reported on the microcomputer study of FEA for recycled plastic composites.

CHAPTER III

Methodology

In the study of composite properties, it is important to define a volume element which is small enough to show the microscopic structural details, yet large enough to represent the overall behavior of the composite. Such a volume element is called the representative volume element or unit cell. A unit cell can consist of a single fiber embedded in a matrix block (Tsai & Hahn, 1980). In this study, the unit cell consisted of a single glass fiber and its surrounding matrix, i.e., high density polyethylene (HDPE). Finite element analysis (FEA) was explored using a microcomputer to fit the needs of the stress analysis on the recycled plastic composites. Special effort was made on the role of glass fiber in the reinforcement of the recycled plastic from the view point of micro-mechanics.

Materials

In this study, the stress analysis of a short fiber (E fiberglass) and the matrix (HDPE) in the composite was addressed. The material properties are presented in the following table:

Table 1. Mechanical properties of constituents

Material	E fiberglass	HDPE
Density (g/cm^3)	2.565 *	0.960 #
Tensile strength (MPa)	3448.3 *	30.3 $
Tensile elastic modulus (GPa)	72.41 *	1.03 $
Poisson's ratio (υ)	0.22 *	0.34 $

* -- Milewski & Katz (1987)
\# -- Quantum Chemical (1990)
$ -- Kaufman & Falcetta (1977)

Computer Software

A finite element analysis software package called Algor was used in this research. Three basic steps were designed in the complete FEA procedures: pre-processing, processing and post-processing.

Pre-processing

Pre-processing involved geometrical modeling and meshing of the composite unit cell to be studied. In order to minimize the computational error, the mesh on the load-bearing surface was made as uniform as possible for all different models. The 6 and 8 node brick elements were used in the modeling (Algor, 1990).

Processing

The Algor processors calculated and analyzed the stress and deformation of the models. There were various processors available in Algor. Each processor performed a different type of analysis. SAP0 (stress analysis processor 0) for linear static analysis was used in this study (Algor, 1992).

Post-processing

After the geometrical modeling of the composite and processing of the model, FEA results can be displayed graphically. The stress distribution can be displayed by using "Stress-di" and "do-dither" functions, which represent different stress levels with different color scales. This function is extremely useful in optimizing part design. Certain areas with excessive stress are typically where mechanical failure will most probably occur. These areas can be reinforced by either increasing the cross sectional area or material strength. Other areas with the least stress may represent the possibility of weight reduction. In this way, the modeled part can be optimized in design.

Analysis

Assumptions

The general assumptions involved in the analysis were the following:

(i) The constituents in the composite exhibited a linear elastic behavior.

(ii) The embedded fibers were transversely isotropic and the surrounding matrix material was isotropic.

(iii) The fiber/matrix interface was a "perfect" bond, so that decohesion did not occur between the two constituents.

The stress field in the unit cell (represented by average stress, $\overline{\sigma_i}$) was defined by Equation 1 (Tsai & Hahn, 1980)

$$\overline{\sigma_i}=\frac{1}{V}\int_V \sigma_i dV=\frac{1}{V}\left[\int_{V_f}\sigma_i dV+\int_{V_m}\sigma_i dV\right] \tag{1}$$

where σ_i is the stress in the unit cell as a function of x, y and z coordinates, V is the total volume of the unit cell, V_f and V_m are the volume of fiber and matrix, respectively.

The volume-average stresses $\overline{\sigma_{fi}}$ in fiber and $\overline{\sigma_{mi}}$ in matrix are defined by Equation 2 and Equation 3 (Tsai & Hand, 1980).

$$\overline{\sigma_{fi}} = \frac{1}{V_f} \int_{V_f} \sigma_i dV \qquad (2)$$

$$\overline{\sigma_{mi}} = \frac{1}{V_m} \int_{V_m} \sigma_i dV \qquad (3)$$

In order to increase the strength of the composite, the fiber is expected to carry more load or stress than the matrix because the glass fiber is approximately one hundred and ten times stronger than the high density polyethylene matrix (both Milewski & Katz, 1987, and Kaufman & Falcetta, 1977). To measure the load-bearing capability of fiber and matrix, a stress partition ratio (SPR) of fiber to matrix was introduced in this paper

$$SPR = \frac{\overline{\sigma_{fi}}}{\overline{\sigma_{mi}}} \qquad (4)$$

where $\overline{\sigma_{fi}}$ and $\overline{\sigma_{mi}}$ are average stress in fiber and matrix, respectively.

From Equation 4, it was noted that when the fiber bore larger stress compared to the matrix, the stress partition ratio would have a higher value. From the view point of composite strengthening, the larger the SPR is, the higher strength the composite will possess.

Effect of Fiber Aspect Ratio (a)

Fiber size is described more generally as aspect ratio, which is the ratio of fiber length to its diameter. In this study, the von Mises criterion was used to measure the principal stresses on both fiber and matrix (Algor, 1990). The equation was given by

$$\sigma_{von\ Mises}=\sqrt{0.5[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2]} \tag{5}$$

where σ_x, σ_y and σ_z are principal stresses along x, y and z axis, respectively.

Figure 1 shows an overview of a typical geometrical model for the composite unit cell. The origin of the coordinate system was defined at the front lower left corner. The total length of the unit cell was divided into 10 units along fiber direction. In this study, the fiber length was kept identical as 101.6 mm (4 in) and was divided into 8 slices along fiber direction for all models and the radius of the fiber

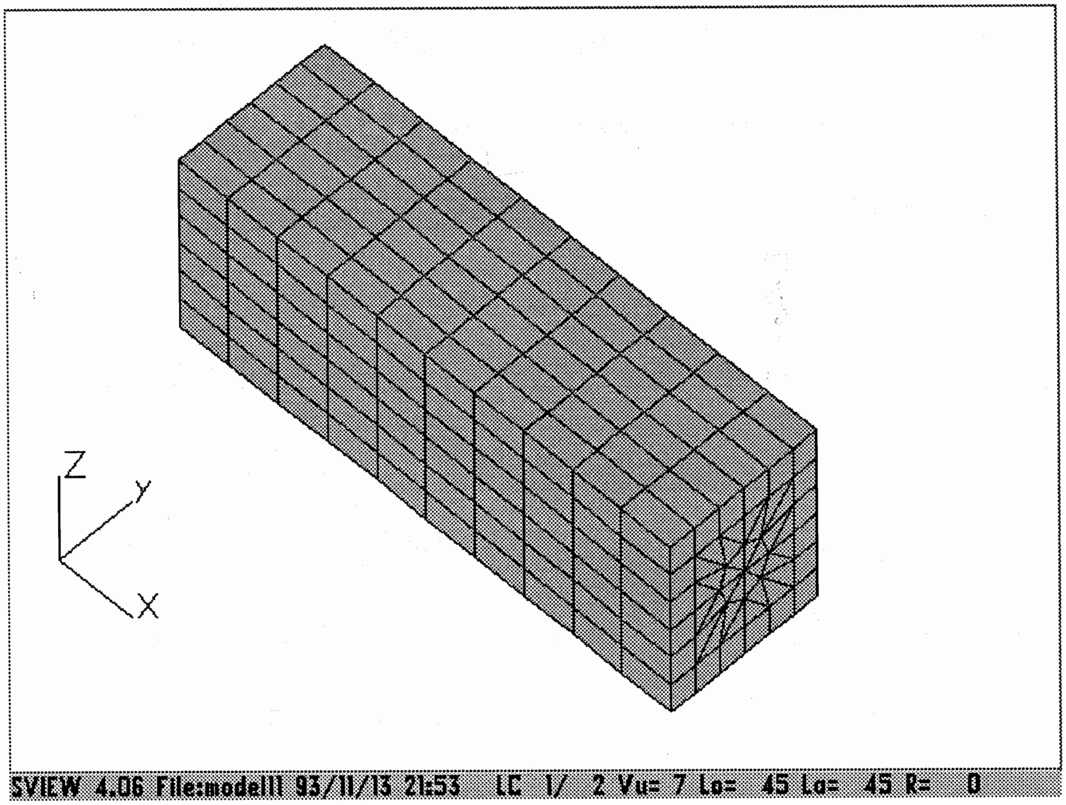

Figure 1. A meshed unit cell with a fiber aspect ratio (a) of 8.

varied from 0.635 mm (0.025 in) to 6.35 mm (0.25 in). Figure 2 depicts a model revealing the relationship between fiber and matrix. The percentage of the fiber was kept as 6.98%. The uniaxial load was added along the fiber direction and the tensile stress applied was 0.138 MPa (20 psi). In order to simulate the boundary conditions, the left end surface of the unit cell was fully constrained.

For calculating the stresses in both fiber and matrix, the whole unit cell was divided into 10 slices along the fiber direction. Figure 3 presents a typical slice of a geometrical model. After processing, the stress of each element can be obtained using "inquire" function. Equations 2 and 3 were followed to calculate the average stresses of fiber ($\overline{\sigma_{fi}}$) or matrix ($\overline{\sigma_{mi}}$) on each slice. The stresses were calculated by volume-integrating the stresses of each element in the fiber (σ_{fi}) or matrix (σ_{mi}) and by dividing the integral results (sum of stress) by the total volume of fiber or matrix in the slice, respectively. The stress partition ratio (SPR) of fiber to matrix for each slice was calculated using $\overline{\sigma_{fi}}$ and $\overline{\sigma_{mi}}$, according to Equation 4.

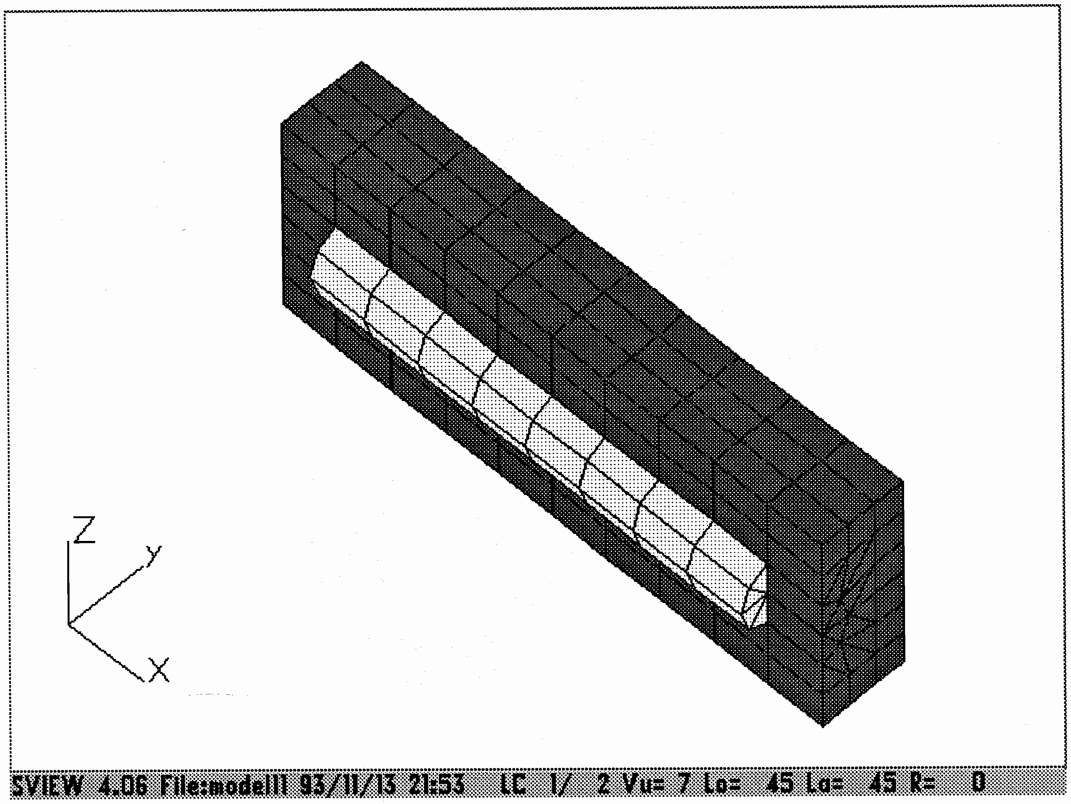

Figure 2. A single glass fiber with a fiber aspect ratio (a) of 8 embedded in high density polyethylene matrix.

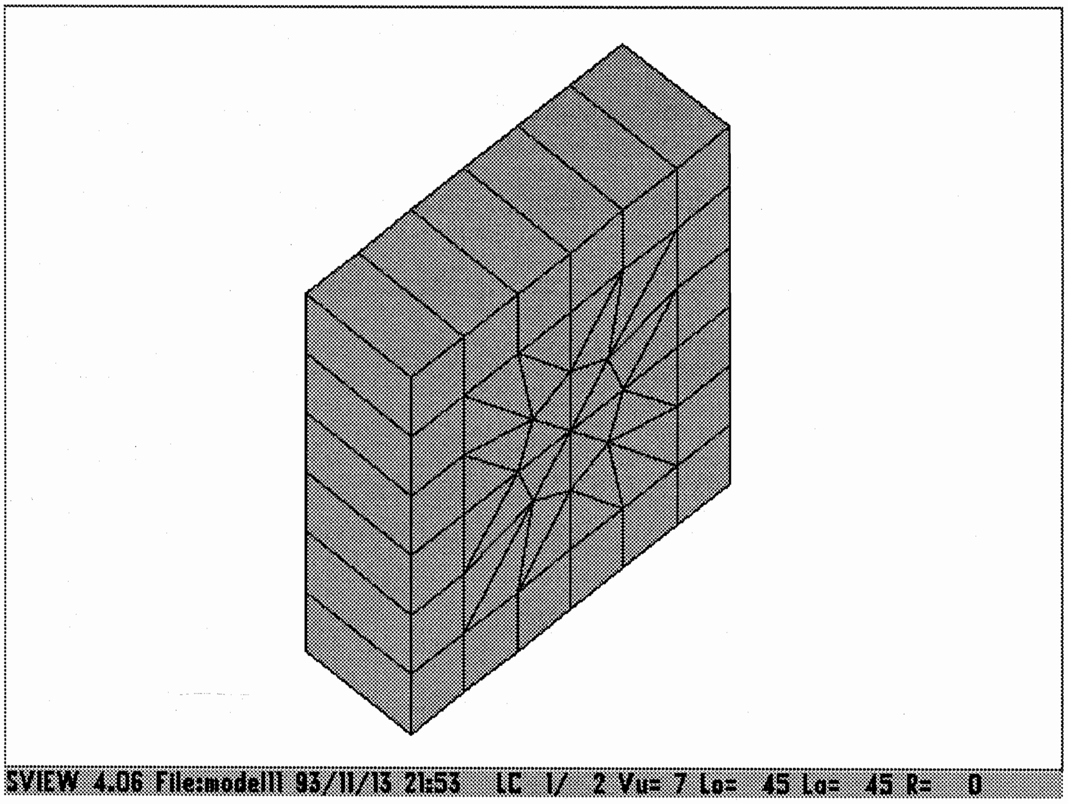

Figure 3. A slice of the unit cell with a fiber aspect ratio (a) of 8.

Effect of Fiber Orientation Angle (A)

In order to investigate the effect of fiber orientation angle on stress distribution in the fiber and the matrix, geometrical models were created with various angles between the fiber axis and the load or x axis. The fiber size was kept the same and the fiber was aligned in the xz plane. Fiber orientation angle $A=0^o$ indicated the fiber along load direction whereas $A=90^o$ represented fiber transversal to load direction.

Figure 4 shows a typical meshed unit cell created to model the effect of fiber orientation on stress distributions in fiber and matrix. Figure 5 depicts a single fiber embedded in high density polyethylene matrix, in which the fiber orientation angle is 15^o between the fiber and the load direction. Von Mises criterion was used to evaluate the principal stress. A slice of the model is shown in Figure 6. Average stresses in fiber and matrix as well as the stress partition ratio (SPR) of fiber to matrix for each slice were analyzed in the same way as in the previous section.

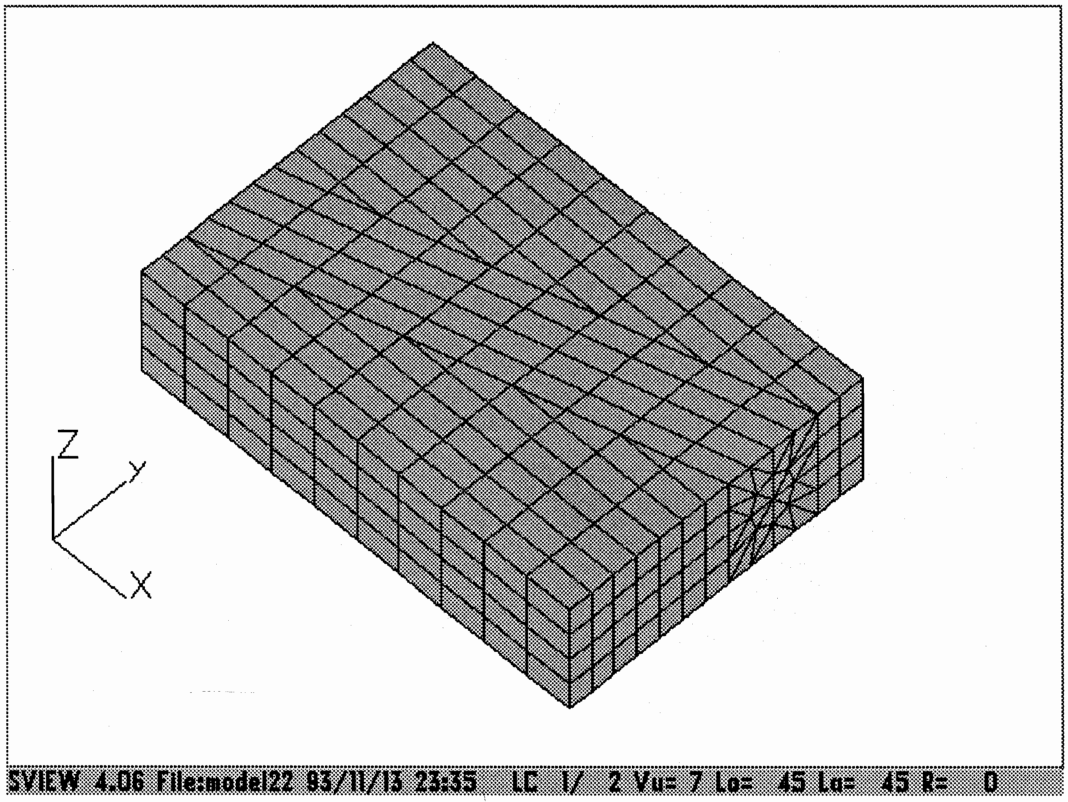

Figure 4. A meshed unit cell with a fiber orientation angle (A) of 15°.

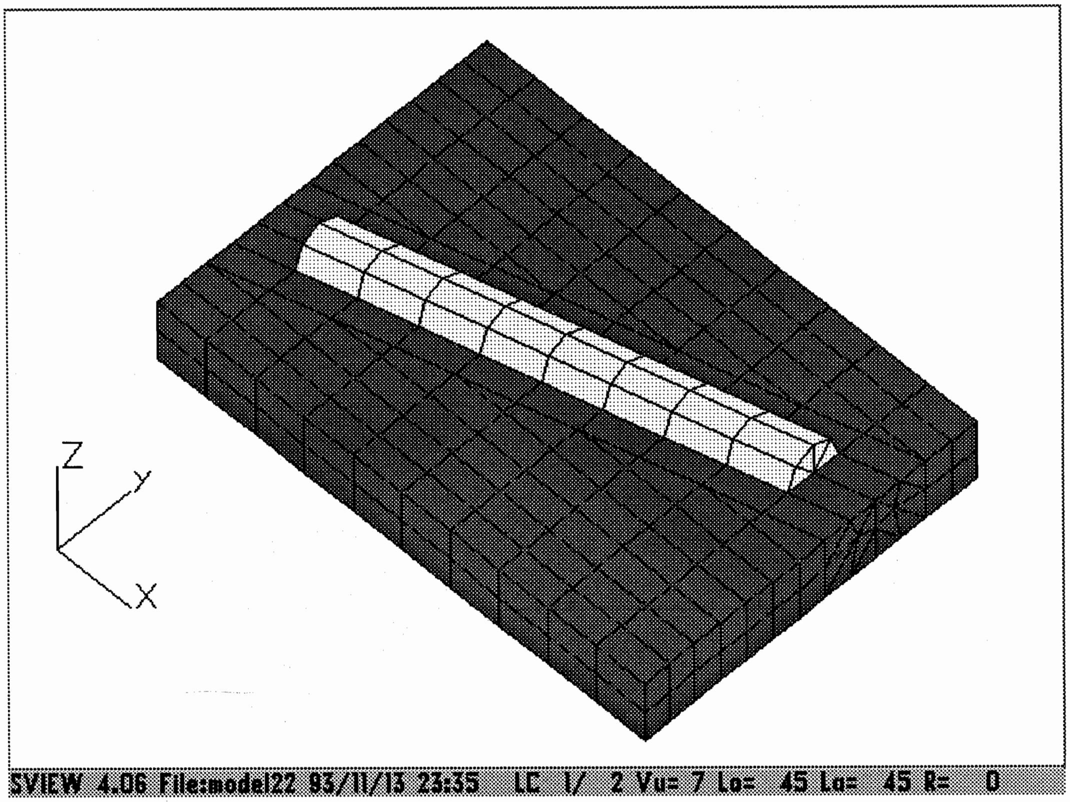

Figure 5. A single glass fiber embedded in high density polyethylene matrix with a fiber orientation angle (A) of 15°.

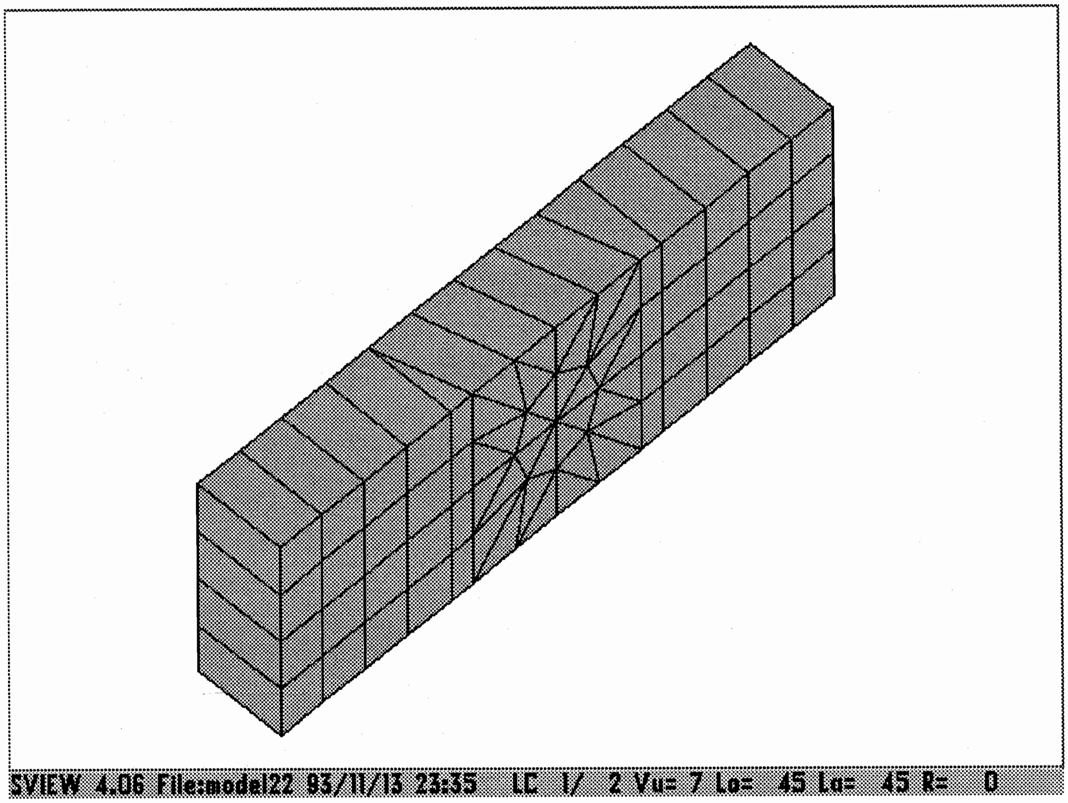

Figure 6. A slice of the unit cell with a fiber orientation angle (A) of 15^{o}.

CHAPTER IV

Results and Discussion

Validation of the Model

In order to validate the finite element models and processor used in this paper, a comparison was made between the predicted elastic properties from the theoretical model by Carman and Reifsnider (1992) and the finite element analysis predictions for short fiber composite in this research. The material properties of the constituents used by Carman and Reifsnider are presented in Table 2.

Table 2. Material properties of constituents in validation model

Material	Tensile modulus (GPa)	Poisson's ratio, υ	Density g/cm^3
Epoxy resin	2.0005 *	.35 *	1.25 #
Steel	190.0000 *	.30 *	7.8 #

*--Carman & Reifsnider (1992)
#--Milewski & Katz (1987)

A finite element model which consisted of a single steel fiber and its surrounding epoxy resin was created with the same conditions as in the analysis by Carman and reifsnider. The fiber aspect ratio was 50 and the volume fraction of fiber in the model was 6%. All geometrical conditions were maintained identical with the models to be used in this study. Using the finite element model, the tensile elastic modulus (E) was calculated. The result (E=6.4 GPa) by Algor finite element model agreed reasonably well with the theoretical prediction (E=6.6 GPa) from the analytical model of Carman and Reifsnider. This agreement suggested that the stress analysis performed by the current model and processor in this research was adequate.

Effect of Fiber Aspect Ratio (a)

Figure 7 shows the variation of average stress in glass fiber with the distance from the left end of the unit cell for three different fiber aspect ratio models. The average stresses were calculated according to equation 2. Generally, the stresses in the fiber were higher for the composite of larger fiber aspect ratio than for the composite of smaller fiber aspect ratio. The maximum stress occurred at the left end of the fiber and the stress decreased as the distance increased. The stress became uniformly higher inside the fiber as the aspect ratio increased. This observation implies that for the best strengthening of

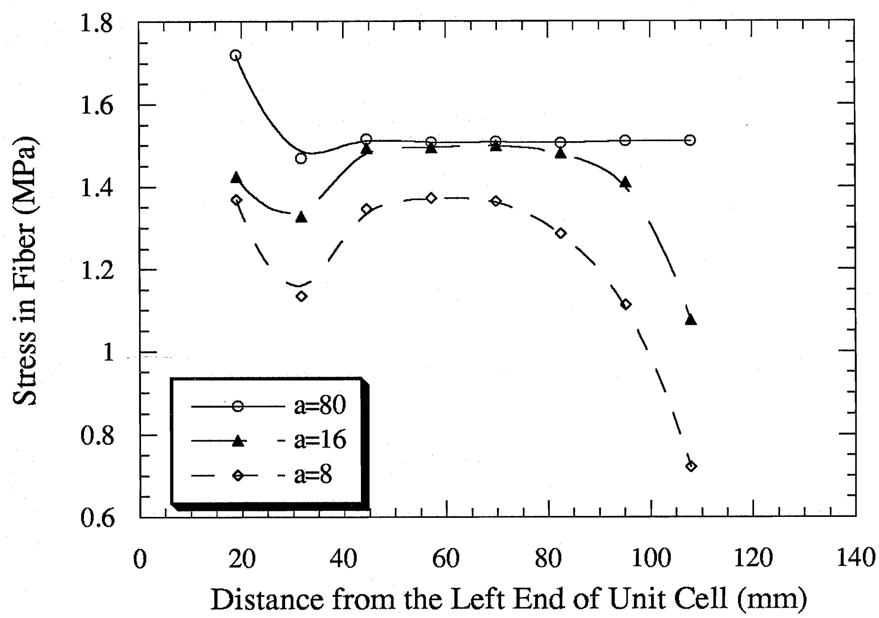

Figure 7. Variation of stress in fiber with the distance from the left end of the unit cell for fiber aspect ratios of 8, 16 and 80.

the composite, a large fiber aspect ratio is desirable.

The stress distribution in matrix is presented in Figure 8 for three fiber aspect ratio models. As the fiber aspect ratio increased, the stress in matrix generally decreased. The stress in matrix (HDPE) was higher where fiber was not present at both ends of the model and reached a minimum and relatively stable value in the middle of the model. This result shows that the fiber with larger aspect ratio carries more load in the composite, which results in lower stress in matrix.

To demonstrate the load bearing capability of the glass fiber, stress partition ratios due to various fiber aspect ratios were calculated along the distance from the left end of the model. The results are shown in Figure 9. The SPR was lower at both ends of the fiber and was maximum in the middle of the composite unit cell. The stress partition ratio was more stable and consistently larger in higher fiber aspect ratio model than in smaller fiber aspect ratio model. The variation of stress partition ratio correlated consistently with the fiber load bearing capability. Fibers with higher aspect ratios have higher stress partition ratios and therefore carry more load.

To further study the effect of fiber aspect ratio (fiber size) on

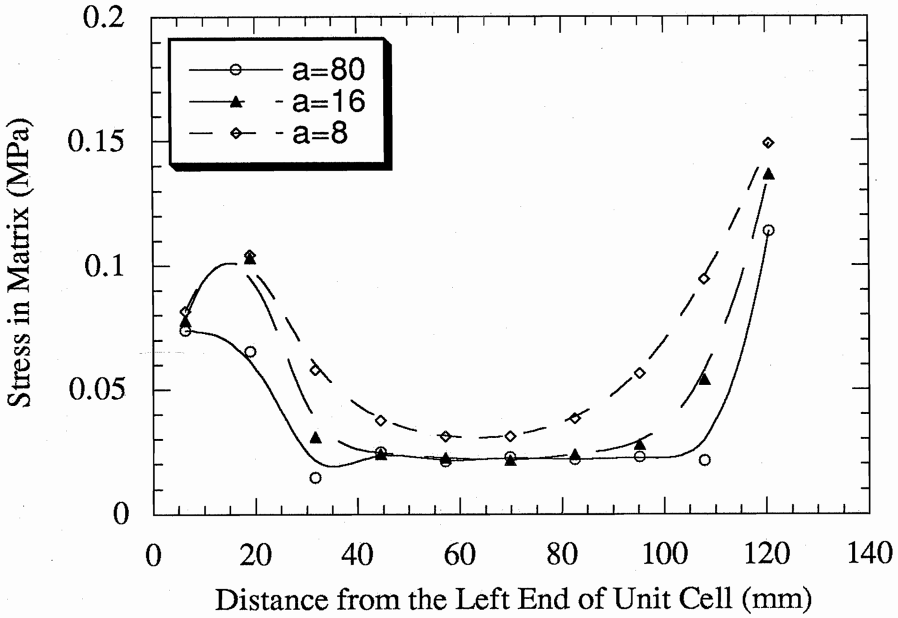

Figure 8. Variation of stress in matrix with the distance from the left end of the unit cell for fiber aspect ratios of 8, 16 and 80.

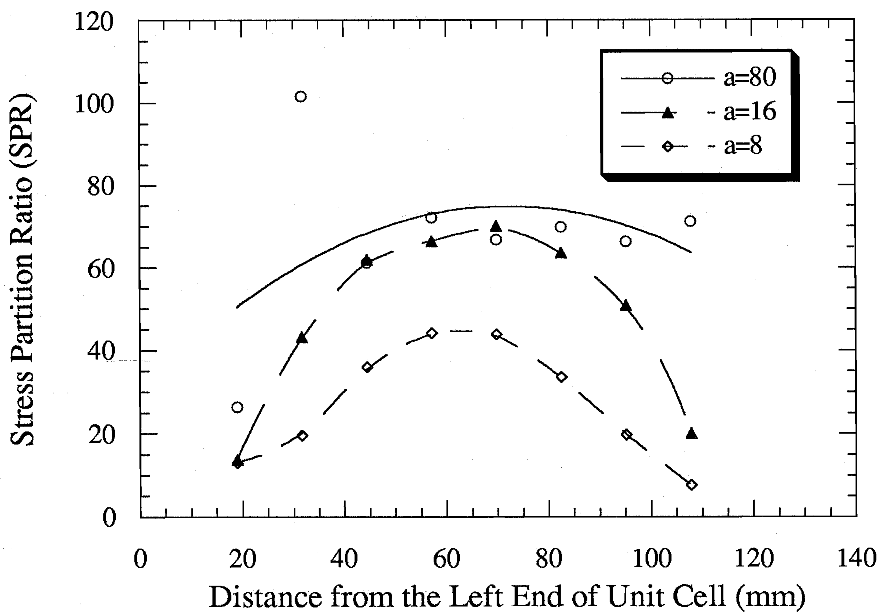

Figure 9. Variation of stress partition ratio (SPR) for fiber aspect ratios of 8, 16 and 80.

the stress distribution in the composite and the strengthening effect of the fiber, average stresses in fiber and matrix as well as stress partition ratio (SPR) in the middle of the unit cell of ten different fiber aspect ratio models were calculated. Figure 10 shows the variation of average fiber stress in the middle of unit cell of the fiber for ten different fiber aspect ratio models. The stress in fiber increased as the fiber aspect ratio increased. After the fiber aspect ratio reached approximately 20, the stress in the fiber tended to be saturated.

Figure 11 shows the stress in matrix versus the fiber aspect ratio, which has a trend exactly opposite to that in the fiber. The stress in the matrix decreased with an increasing fiber aspect ratio (a) up to approximately 20. Then the slope of change became very flat. Moreover, it should be pointed out that the stress in the high density polyethylene matrix was much lower than that in the glass fiber.

The stress partition ratio in the middle of the unit cell is shown in Figure 12 for ten different fiber aspect ratio models. The SPR increased with fiber aspect ratio up to 20 and then leveled off. The maximum stress partition ratio in the composite of high density polyethylene reinforced with glass fiber was close to 73. It was noted

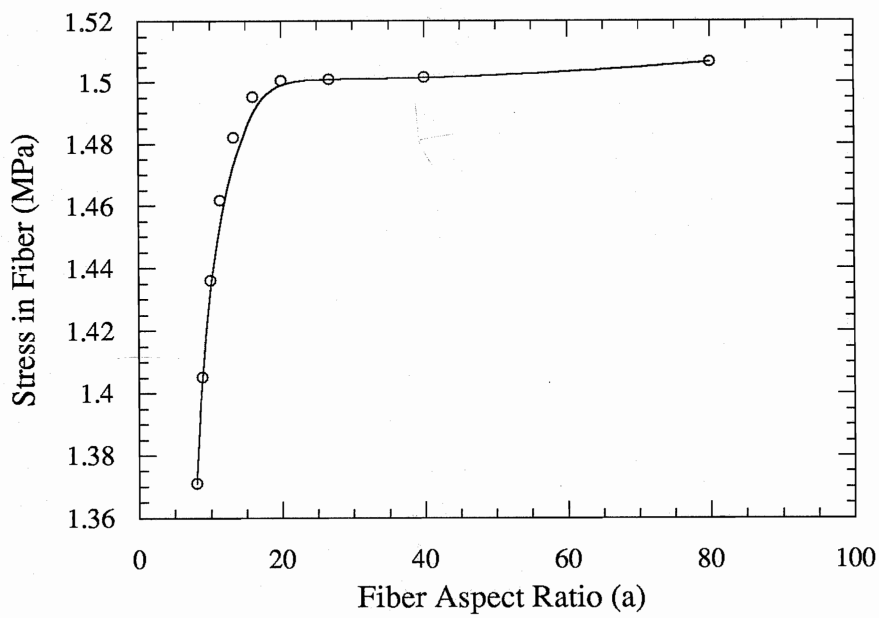

Figure 10. Variation of average fiber stress in the middle of the unit cell with various fiber aspect ratios.

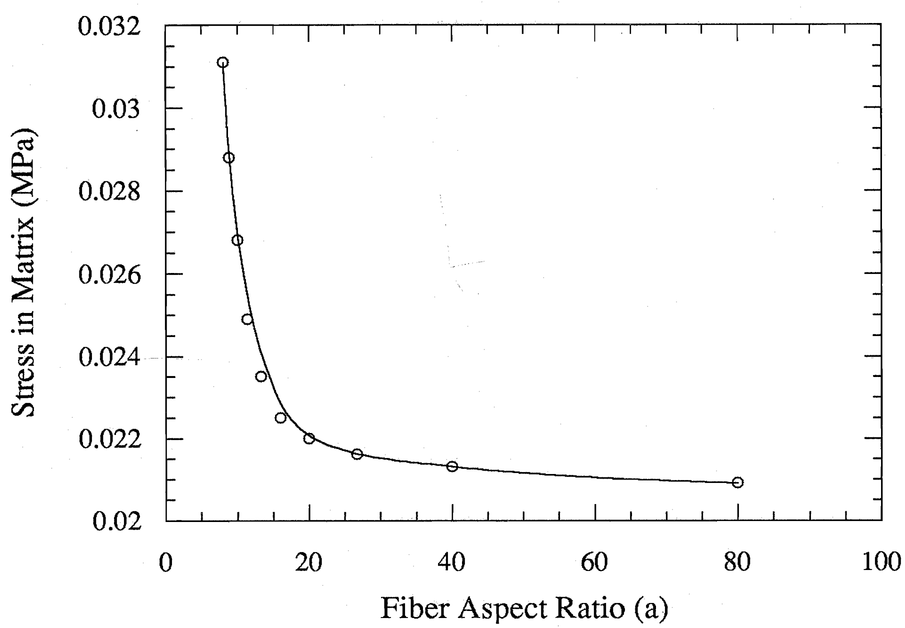

Figure 11. Variation of average matrix stress in the middle of the unit cell with various fiber aspect ratios.

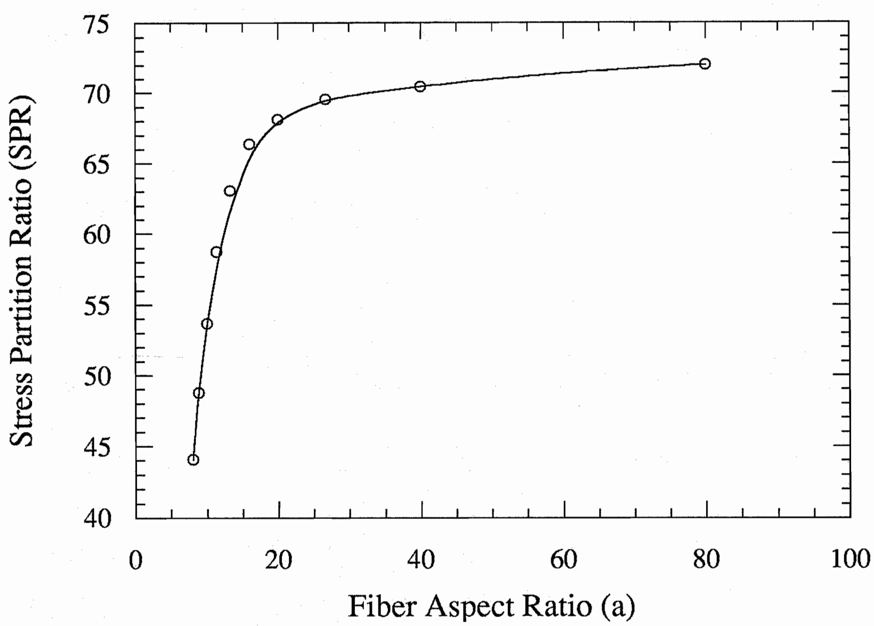

Figure 12. Variation of stress partition ratio (SPR) in the middle of the unit cell with various fiber aspect ratios.

from Table 1 that the tensile strength of glass fiber was approximately 110 times larger than that of high density polyethylene matrix. Thus, considering the actual fluctuation, fatigue behavior and actual production cost of the glass fiber, a fiber aspect ratio of 20 may receive an optimum pay-off from the reinforcing glass fiber. Further increase in fiber aspect ratio may slightly increase the stress partition ratio but the rate of increase was drastically reduced. Therefore, a conclusion can be drawn that the fiber aspect ratio of 20 for glass fiber may give the optimum strengthening of the composite.

Effect of Fiber Orientation Angle (A)

Figure 13 presents the variations of average stress in glass fiber with the distance from the left end of the unit cell in the fiber direction for two fiber orientation angles $A=0^{o}$ and $A=15^{o}$. The average stress was calculated according to equation 2. Generally, the stress in fiber was higher for $A=0^{o}$ model than for $A=15^{o}$ model. For the composite with $A=0^{o}$, the highest stress occurred at the left end of the fiber and the lowest stress was at the other end of the fiber. However, for the composite with $A=15^{o}$, the maximum stress occurred in the middle of the fiber and the lowest stress occurred at

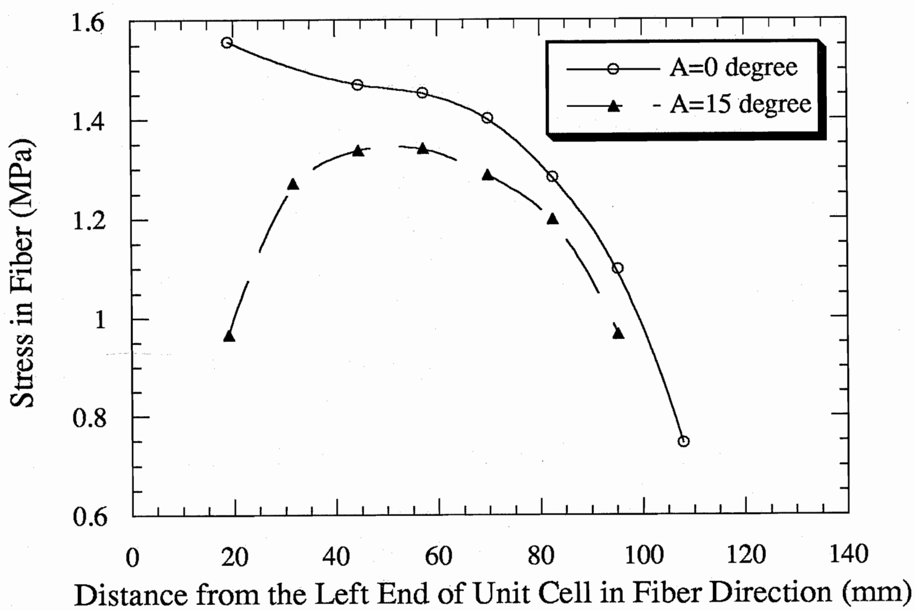

Figure 13. Variation of stress in fiber for fiber orientation angles of 0^{o} and 15^{o}.

both ends of the fiber. The stress in fiber decreased as the fiber orientation angle increased. This result implies that the strength of the composite with $A=0^o$ is higher than that of the composite with $A=15^o$.

The comparison of average stress in matrix (HDPE) between the composite with $A=0^o$ and the composite with $A=15^o$ is presented in Figure 14. In the angle $A=15^o$ model, the average stress in matrix was generally higher than that in the angle $A=0^o$ model. For both cases, the lowest stress occurred in the middle of the unit cell and the highest stress occurred at the right end of the unit cell. The stress was relatively higher at the left end of the unit cell where the fiber did not exist than that in the middle. The observation shows that when orientation angle $A=0^o$, the fiber of the composite carries more load, which results in lower stress in matrix.

In order to investigate the load bearing capability of the glass fiber, the stress partition ratio (SPR) of the composites with fiber orientation angle $A=0^o$ and $A=15^o$ were calculated along the fiber direction. Figure 15 shows the variation of stress partition ratio (SPR) with distance from the left end of the unit cell along fiber

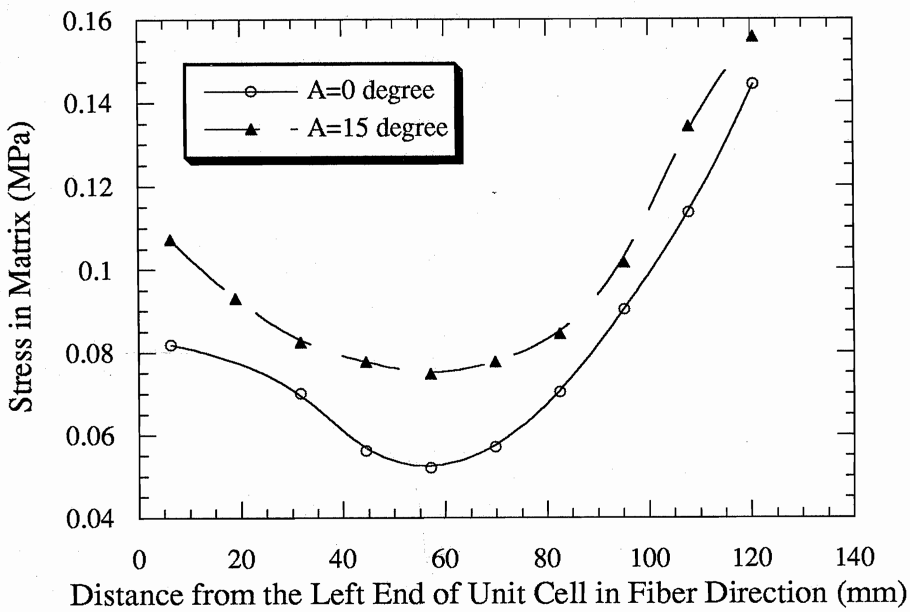

Figure 14. Variation of stress in matrix for fiber orientation angles of 0^o and 15^o.

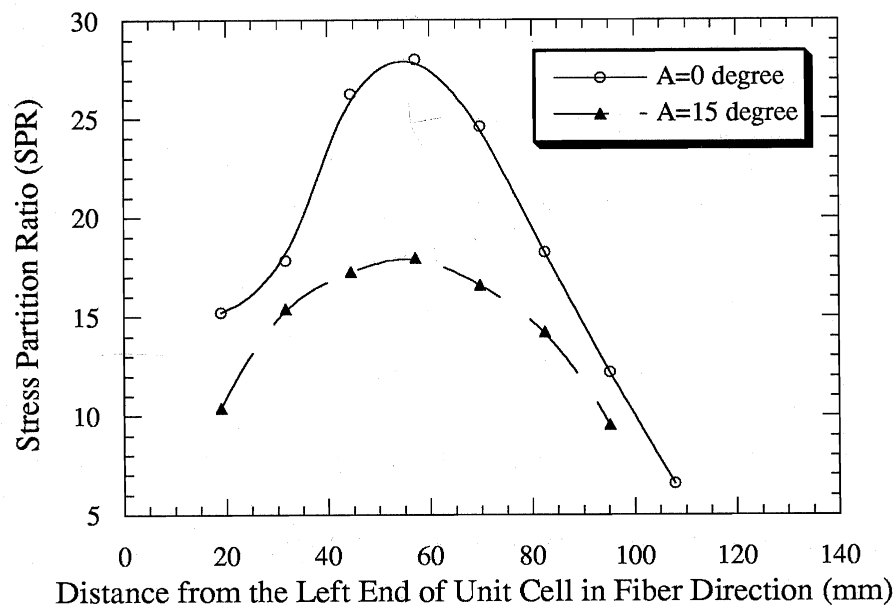

Figure 15. Variation of stress partition ratio (SPR) for fiber orientation angles of 0^{o} and 15^{o}.

direction. It was found that in general, the stress partition ratio (SPR) was higher in the composite with $A=0^o$ than in the composite with $A=15^o$. This result implies that the fiber in composite with $A=0^o$ could carry more load than the fiber in the composite with $A=15^o$. For both composites, the highest SPR was close to the middle of the unit cell and the lowest SPR was located at the right end of the unit cell.

To further investigate the effect of the fiber orientation on the stress distribution in the composite and the strengthening effect of the fiber, average stress in both the fiber and matrix as well as stress partition ratio (SPR) in the middle of seven different fiber orientation angle models were calculated. Figure 16 demonstrates the stress distribution in fiber for the models with various fiber orientation angles. It was found that as the angle increased, the stress in fiber decreased and reached the lowest value at the point of $A=75^o$. Though the stress was higher at $A=90^o$ than that at $A=75^o$, it was much smaller than the stress at $A=0^o$. This prediction agrees well with the results of Hom's study (1992). The observation indicates that when the fiber orientation is the same as the load direction

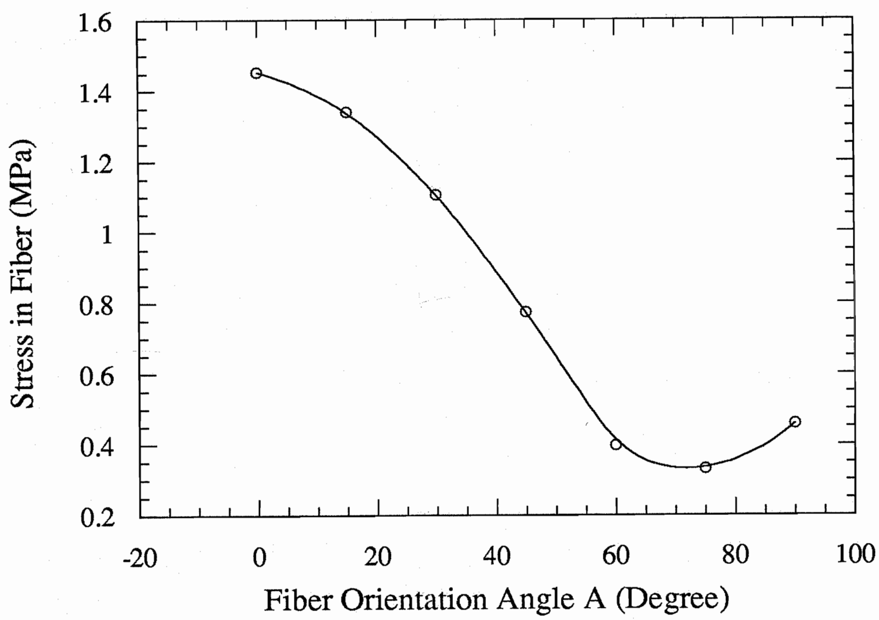

Figure 16. Variation of average fiber stress in the middle of the unit cell with various fiber orientation angles.

(orientation angle equals 0^o), the best strengthening of the composite will be obtained.

Figure 17 shows the average stress in matrix versus various fiber orientation angles. The stress increased as the angle increased and reached the maximum at $A=75^o$. The lowest matrix stress occurred in the composite with angle $A=0^o$. In addition, the stress in the high density polyethylene matrix was much lower than that in glass fiber.

The stress partition ratio (SPR) is shown in Figure 18 for the composites with different fiber orientation angles. The stress partition ratio (SPR) decreased as the angle increased and the lowest point occurred when the fiber orientation angle was approximately $A=75^o$. The maximum stress partition ratio was close to 28 when the fiber orientation angle equals to 0^o. It is concluded that the fibers oriented in the tension load direction provides the optimum strength of the composite.

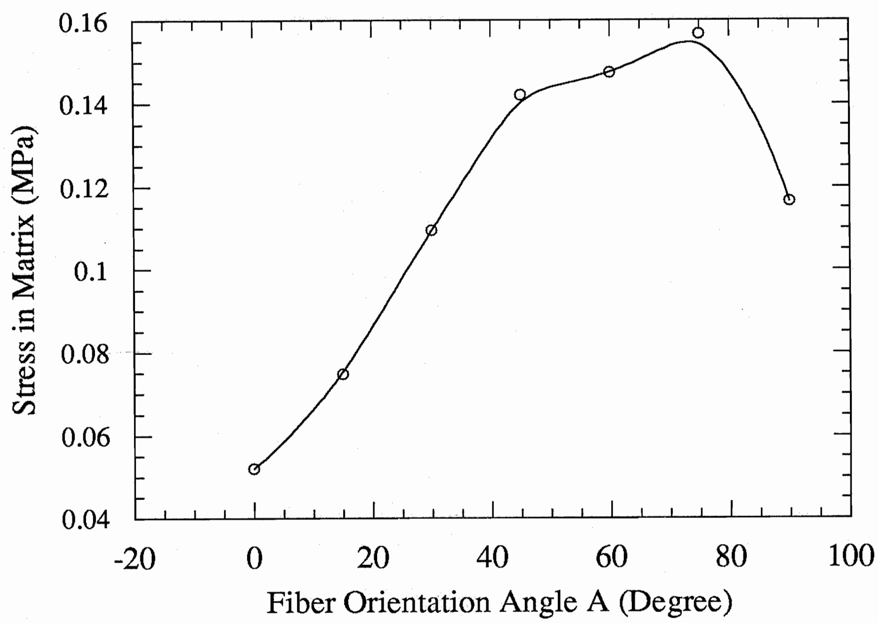

Figure 17. Variation of average matrix stress in the middle of the unit cell with various fiber orientation angles.

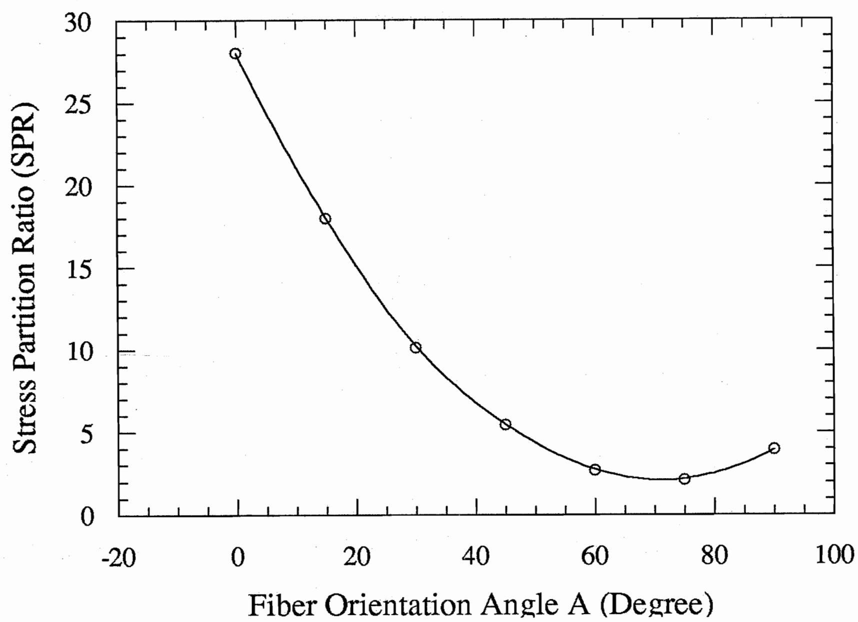

Figure 18. Variation of stress partition ratio (SPR) in the middle of the unit cell with various fiber orientation angles.

CONCLUSIONS

The following conclusions were made according to the finite element analysis on glass-fiber-reinforced thermoplastic composite of recycled high density polyethylene.

1. The geometrical model and Algor processor were proven to be adequate for the analysis of the thermoplastic composite.

2. A stress partition ratio (SPR) has been introduced successfully to evaluate the load bearing capability of fibers in the composite.

3. As the fiber aspect ratio increased up to 20, the stress in the fiber increased, the stress in the matrix (HDPE) decreased and therefore the stress partition ratio increased. The aspect ratio of 20 for glass fiber may give the optimum strength of the composite.

4. As the fiber orientation angle increased, the stress in the fiber decreased and the stress in the matrix increased. Those changes resulted in the decrease of stress partition ratio as the fiber orientation angle increased. Fibers aligned in tension load direction provided the best load carrying capability.

RECOMMENDATIONS FOR FURTHER STUDY

The following recommendations for further study were made according to this research:

1. In order to improve the efficiency of the analysis, a computer program which can automatically acquire element stress and calculate the average stress in fiber and matrix for each model can be developed.

2. The effect of fiber distribution on the stress in the fiber and matrix of the composite is recommended to be investigated using Algor finite element analysis.

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